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MEGARIPPLE MIGRATION IN THE NEARSHORE

by

Angela Holcombe Walker

December 1999

Thesis Advisor:	Edward B. Thornton
Thesis Co-Advisor:	Edith L. Gallagher

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Seafloor morphology in the surf zone of a sandy ocean beach was measured nearly continuously for 2 months with a 1.4 X 1.4 m coherent array of 7 sonar altimeters. Migrating megaripples, seafloor bedforms with amplitudes of O(10-50 cm) and lengths of O(1-5 m), were observed in about 2 m water depth in the trough between a sand bar and the shoreline for a wide range of wave and current conditions. Megaripple migration speed and direction are estimated from the array data using cross-correlations between seafloor elevation time series observed along the cross- and alongshore array legs. Megaripples were shown to be aligned in a direction that maximized the gross sediment transport normal to the bedform crest (Rubin and Hunter, 1987; Gallagher, *et al.* 1998). It is hypothesized that megaripple migration rate is related to the net transport in the direction of bedform alignment. The speed of megaripple migration is compared with the magnitude of the velocity field normal to the bedform crest in the direction of the mean, wave orbital, and resultant velocities.

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MEGARIPPLE MIGRATION IN THE NEARSHORE

Angela Holcombe Walker
Lieutenant, United States Navy
B.S., University of Florida, 1992

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Author: Angela Holcombe Walker

Approved by: Edward B. Thornton, Thesis Advisor

Edith L. Gallagher, Thesis Co-Advisor

R.W. Garwood, Chairman
Department of Oceanography

ABSTRACT

Seafloor morphology in the surf zone of a sandy ocean beach was measured nearly continuously for 45 days with a 1.4 X 1.4 m coherent array of 7 sonar altimeters. Migrating megaripples, seafloor bedforms with amplitudes of O(10-50 cm) and lengths of O(1-5 m), were observed in about 2 m water depth in the trough between a sand bar and the shoreline for a wide range of wave and current conditions. Megaripple migration speed and direction are estimated from the array data using cross-correlations between seafloor elevation time series observed along the cross- and alongshore array legs. Megaripples were shown to be aligned in a direction that maximized the gross sediment transport normal to the bedform crest (Rubin and Hunter, 1987; Gallagher, *et al.* 1998). It is hypothesized that megaripple migration rate is related to the net transport in the direction of bedform alignment. The speed of megaripple migration is compared with the magnitude of the velocity field normal to the bedform crest in the direction of the mean, wave orbital, and resultant velocities.

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I. INTRODUCTION

Megaripples are bedforms with heights of 10 - 50 cm and lengths of 1 - 5 m. These features are important because they affect bedload transport, sediment suspension, boundary layer turbulence generation, energy dissipation of waves, and currents via form drag. Few observations of bedforms in the nearshore exist because the surf zone is a difficult environment in which to make measurements. Clifton *et al.* (1971) and Clifton (1976) made measurements of bedforms on beaches in Oregon using SCUBA during mild conditions. They observed megaripples (Figure 1) both inside the surf zone (i.e. in the bar-trough) and outside the breaking waves (Figure 2). Clifton *et al.* (1971) determined lunate megaripples migrated towards the shore at an average rate of 30 cm/hr during low-energy conditions. Clifton (1976) proposed the onshore migration was a result of sediment transport associated with asymmetries in wave velocities. They concluded that these structures are common in medium- to coarse-grained sand under conditions of intense asymmetric flow generated by long period waves and are common in 2 - 4 m of water. Hay and Wilson (1994) observed similar crescent shaped bedforms using a fixed rotating sidescan sonar. Hay and Wilson (1994) and Hay and Bowen (in press) observed migration rates between 0.5 to 3 cm/hr

during both low and high wave energy conditions. During a storm Hay and Bowen (in press) found a strong relationship between alongshore current speed (20 to 80 cm/s) and alongshore megaripple migration rate, O(3 cm/hr). Gallagher *et al.* (1998b) compared megaripple migration direction with the direction of waves, mean currents, and their vector sum as well as with a model for desert dune orientation (Rubin and Hunter, 1987). They found that the model, which is based on instantaneous flow vectors, was a better predictor of migration direction than any time averaged flow parameter (mean, root mean square (rms), and their vector sum).

If migration of bedforms is an important mechanism for bedload sediment transport, then the understanding of megaripple migration in oscillatory flow is fundamental to understanding nearshore hydrodynamic and sediment processes. When they migrate, they may be an important mechanism for sediment transport. The relationship between the migration rate of megaripples and wave and current forcing is studied in this thesis.

II. DUCK94 EXPERIMENT

The measurements were obtained during DUCK94, between 01 September 1994 through 15 October 1994 at the U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck, North Carolina. The DUCK94 field experiment was a pilot study, which represented a first attempt to make quantitative multi-scale measurements of nearshore morphology (Thornton *et al.*, 1998). The FRF is located on the Outer Banks, a barrier island formation with no major coastal structures that can interfere with nearshore flows. The mean amplitude of the semidiurnal tide is approximately 0.5 m. Fine quartz sediments within the surf zone are fairly well sorted with a mean grain size of 0.2 mm while sediments on the foreshore are poorly sorted with larger mean grain sizes usually greater than 0.4 mm.

Observations of migrating megaripples were made in the surf zone using an array of seven 1 MHz downward-looking automatic gain control (AGC) sonar altimeters (Figure 3). Sonar altimeters estimate the location of the seafloor by measuring the time for an acoustic pulse to travel to the seafloor and back and then converting the time to a distance using the theoretical speed of sound. The AGC can accurately estimate the seafloor location to within ± 3 cm

even in the surf zone where energetic breakers and strong currents produced bubbles and dense sediment suspension (Gallagher *et al.*, 1996).

The array was located approximately 50 m from the shoreline in 1.5 to 2 m of water depth (Figure 4) in the trough between the sand bar and the beach (Figure 3a). Wave height ranged from 0.5 to 4 m with three large storms (02 - 05 September, 02 - 04 October, and 10 - 20 October) occurring during the experiment (Figures 5 and 6). An electromagnetic current meter, which measured cross- and alongshore components of the fluid velocity at 2 Hz was co-located with the array and was about 0.5 m above the bed (Figure 3b). During storms, both wave orbital velocities (indicated by U_{rms}) and steady currents (U_{mean}, V_{mean}) were large, O(1 m/s) (Figure 7). During periods of low energy waves (wave height < 1 m), currents were negligible and RMS currents were small, O(25 cm/s). Megaripples were observed to exist about 60% of the time and under a variety of conditions.

III. THEORY AND METHODOLOGY

Traditionally, sediment bedforms in directionally varying flow have been classified as transverse, longitudinal, or oblique by their alignment with the resultant transport vector (normal, parallel, or neither). Rubin and Hunter (1987) proposed that gross transport should be considered since all transport can build bedforms even if the net or resultant is zero (i.e. purely oscillatory flow). They hypothesized that bedforms are aligned such that the gross sediment transport normal to their crests is maximized.

To predict the orientation of the bedforms, the absolute value of the components of the two transporting flows normal to the bedform crests are added,

$$T = D\left|\sin\alpha\right| + S\left|\sin(\gamma - \alpha)\right| \tag{1}$$

where D and S are the dominant and subordinate vectors of the two flows, α is the angle between D and the bedform crest, and γ is the divergence angle between D and S (Figure 8). The first derivative is applied to find the value of α which maximizes T,

$$tan\,\alpha = \pm\frac{\frac{|D|}{|S|} + |cos\,\gamma|}{|sin\,\gamma|}. \qquad (2)$$

Rubin and Hunter (1987) tested the alignment of subaerial bedforms in bi-directional flow by using a rotating bed in a unidirectional flow. They found good agreement between their hypothesis and the rotating bed experiment. The results showed that for a given pair of flow vectors, D and S, the bedforms aligned such that the gross bedform normal transport was maximized. Rubin and Ikeda (1990) studied the alignment of subaqueous dunes in a laboratory experiment and similarly found, "The bedforms had the orientation that was subject to more transport crossing the bedform crestline than any other possible bedform orientation." They also learned two important requirements of this model: 1) the transporting vectors must be temporally distinct, and 2) they must be relatively short enough in duration that the bedforms do not come into equilibrium with either transporting flow.

Gallagher *et al.* (1998b) applied this theory to field observations made in the surf zone during the DUCK94 experiment. Observed megaripple migration rate was calculated quantitatively by estimating the time-lag between

altimeter pairs from the maximum cross-correlation. A sample of the time series from three sonars in the cross-shore leg of the array are shown in Figure 9. The three panels are positioned relative to the actual spacing (where the top panel is from the most onshore altimeter) and the line drawn between similar features illustrates a 30 cm/hr migration rate. Overlapping 48-hour-long time series (e.g. Figure 9) were used to estimate megaripple migration speeds and directions for the two month long experiment (when megaripples existed).

To apply Rubin and Hunter (1987) to nearshore forcing, D and S need to be properly represented. In the nearshore, mean and oscillatory currents are traditionally separated and treated as different forcing mechanisms for sediment transport. However, they are not temporally distinct, and thus can not be used to represent D and S. Gallagher *et al.* (1998b) used the onshore wave surge (plus any coincident mean flow) and the offshore wave surge (plus any coincident mean flow) to represent D and S and to predict orientation of bedforms. This representation gives temporally distinct vectors. In addition, the time required for megaripples to equilibrate, O(hrs), is long compared with wave velocities, O(secs), thus the model is valid for use in the surf zone.

To parameterize the onshore and offshore surge of the waves from measured currents sampled at 2 Hz, instantaneous

transport was approximated by the magnitude of the instantaneous velocity cubed

$$Q \propto \sqrt{\left(U^2+V^2\right)}^3 \tag{3}$$

(after common transport models, e.g. Bailard, 1981). These instantaneous transport vectors were sorted into 5° bins then summed over a 3-hour period given a directional distribution of cumulative transport (Figure 10). Using these cumulative transport vectors, bedform orientation was found by numerically solving for bedform orientation, α, for which the *gross bedform normal (GBN) transport* was maximized

$$T_{GBN} = \sum_{i=1}^{72} Q_i \left| sin(\alpha - \gamma_i) \right| \tag{4}$$

where i represents each 5° bin. The 3-hour estimates were then averaged to give overlapping 48-hour estimates of bedform orientation for comparison with observed megaripple migration direction.

The observed megaripple migration direction, θ_{Mrip}, are compared with the predicted direction, θ_{RH}, in Figure 11 where

$$\theta_{RH} = 90° - \alpha \ . \tag{5}$$

Gallagher *et al.* (1998b) found that the oriention of nearshore megaripples is explained by Rubin and Hunter's model of subaerial dune migration direction.

Here, it is hypothesized that megaripple migration rate is related to the net transport in the direction of bedform alignment. This net bedform normal transport is calculated by summing the directional bin components, which are normal to the predicted θ_{RH} such that

$$Net\, T_{GBN} = \sum_{i=1}^{72} Q_i \, sin(\alpha - \gamma_i) \tag{6}$$

where i represents each 5° bin. Note that it is now possible to obtain positive and negative migration rates since we include the directionality of the normal component. Again, 3-hour estimates of megaripple migration rate were averaged to give overlapping 48-hour estimates for comparison with observed megaripple migration rates.

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IV. ANALYSIS

Measured velocities are used to parameterize the flow field for comparison with observed megaripple migration rates. The measured cross- (U) and alongshore (V) fluid velocities were separated into mean and wave (oscillatory) 1-hour averages

$$U = \overline{u} + \tilde{u} \tag{7}$$

$$V = \overline{v} + \tilde{v} \tag{8}$$

where the bar and the tilde represent the mean and wave velocities respectively. Next, hourly skewness-weighted rms wave velocities were calculated

$$u_{skew} = \frac{\left\langle \tilde{u}^3 \right\rangle}{\left\langle \tilde{u}^2 \right\rangle} \tag{9}$$

$$v_{skew} = \frac{\left\langle \tilde{v}^3 \right\rangle}{\left\langle \tilde{v}^2 \right\rangle} \tag{10}$$

where $\langle\ \rangle$ denotes time averaging. Hourly mean and skewness-weighted rms wave velocities were then averaged for three hours

$$\bar{u}_3, \bar{v}_3 = \langle \bar{u} \rangle, \langle \bar{v} \rangle \tag{11}$$

$$\tilde{u}_3, \tilde{v}_3 = \langle u_{skew} \rangle, \langle v_{skew} \rangle \; . \tag{12}$$

Magnitudes for 3-hour mean velocities, skewness-weighted rms wave velocities, and the vector sum of the mean and wave velocities were calculated

$$\bar{U}_3 = \sqrt{\bar{u}_3^2 + \bar{v}_3^2} \tag{13}$$

$$\tilde{U}_3 = \sqrt{\tilde{u}_3^2 + \tilde{v}_3^2} \tag{14}$$

$$U_3 = \sqrt{(\bar{u}_3 + \tilde{u}_3)^2 + (\bar{v}_3 + \tilde{v}_3)^2} \; . \tag{15}$$

Finally, 48-hour magnitudes of the mean, the skewness-weighted rms wave, and the vector sum were calculated for 16 sequential 3-hour magnitudes

$$\bar{U}_{48} = \langle \bar{U}_3 \rangle \tag{16}$$

$$\tilde{U}_{48} = \langle \tilde{U}_3 \rangle \tag{17}$$

$$U_{48} = \langle U_3 \rangle \tag{18}$$

in order to compare with the 48-hour observed megaripple migration rates.

V. RESULTS AND CONCLUSIONS

Observed megaripple migration speeds are plotted in Figure 12 verses the cube of the mean ($\overline{U}_{48}$), skewness-weighted rms wave ($\tilde{U}_{48}$), and vector sum (U_{48}) velocities in addition to the predicted *net gross bedform normal transport*, *Net* T_{GBN}. Results were not sensitive to the exponent (2, 3, 4, or 6) in the model used to represent instantaneous sediment transport (Q in Equation 3 and Q_i in Figure 10). The correlation coefficient values, r, are similar for $\overline{U}_{48}$, U_{48}, and *Net* T_{GBN}, and all the r values are statistically significant at the 95% confidence level. Therefore, results do not suggest that one transport formulation is best.

There are roughly two populations of data points. One corresponds to a current-dominated period where megaripple speeds are greater than about 60 cm/hr, while the other period is wave-dominated with megaripple speeds less than about 60 cm/hr. In panels (a), (c), and (d), the current-dominated points all correspond to large transport estimates, so megaripple speeds could be dependent, at least crudely, on any of these three transport parameters. In general, these observations suggest that high megaripple

speeds correspond to high current velocities when sediment transport is large and low speeds correspond to low current velocities when less sand is in motion. This result is in general agreement with the results of Hay and Bowen (in press) who also observed migrating megaripples during DUCK94. They focused on a three day-long, high-energy event during which they found that megaripple migration rates were a strong function of the observed steady currents.

For low-energy periods when oscillatory wave velocities are dominant and megaripple migration is slow, there is no strong relationship between megaripple speed and $\tilde{U}_{48}$ (Figure 12b). Improved models for sediment transport, which perhaps include acceleration (Clifton, 1976; Gallagher *et al.*, 1998a), might improve this relationship.

These results suggest that during periods of high-energy waves, megaripple migration rates are higher than during periods of low-energy waves. Thus, the hypothesis that megaripple migration rate is related to transport is supported by the analysis of this data set. The hypothesis that *net* transport in the direction of bedform alignment following Rubin and Hunter (1987) and Gallagher *et al.* (1998b) would be the best predictor of megaripple speed is not supported. However, the prediction of sediment transport via megaripple migration requires a vector, that is, both direction and magnitude. Thus, the model of Rubin

and Hunter (1987) is a better tool for predicting bedform migration. More study in this area is required in order to better understand bedform processes and sediment transport in the nearshore.

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APPENDIX: FIGURES

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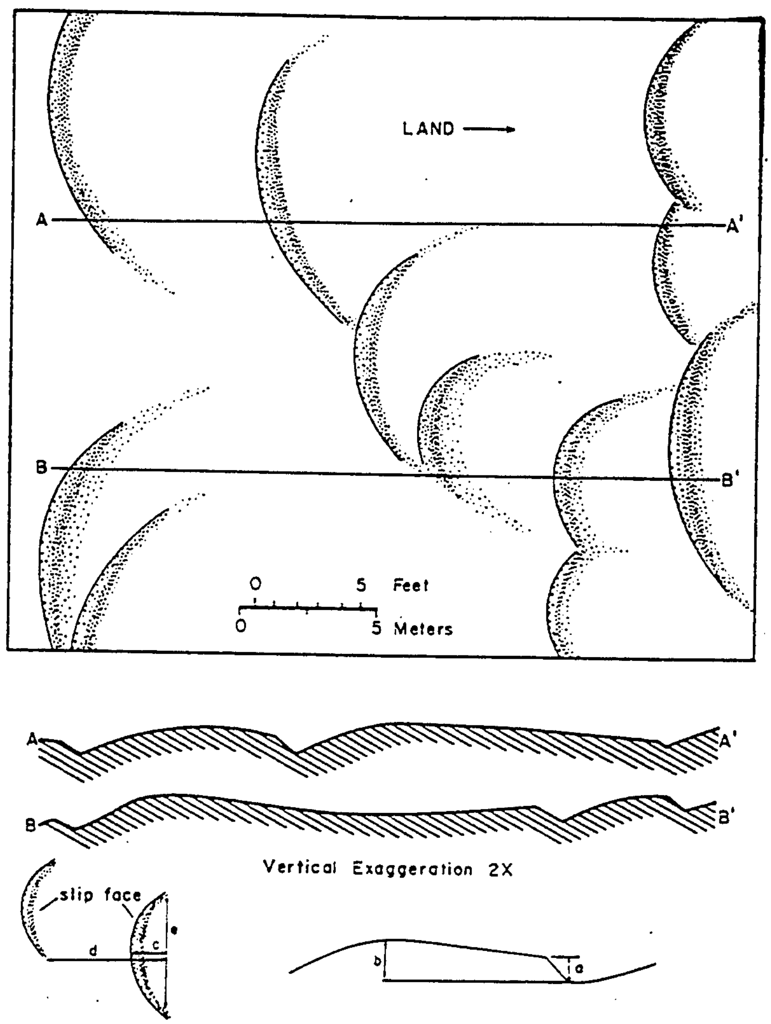

Figure 1. Plan view and profile across lunate megaripples (Clifton *et al.*, 1971).

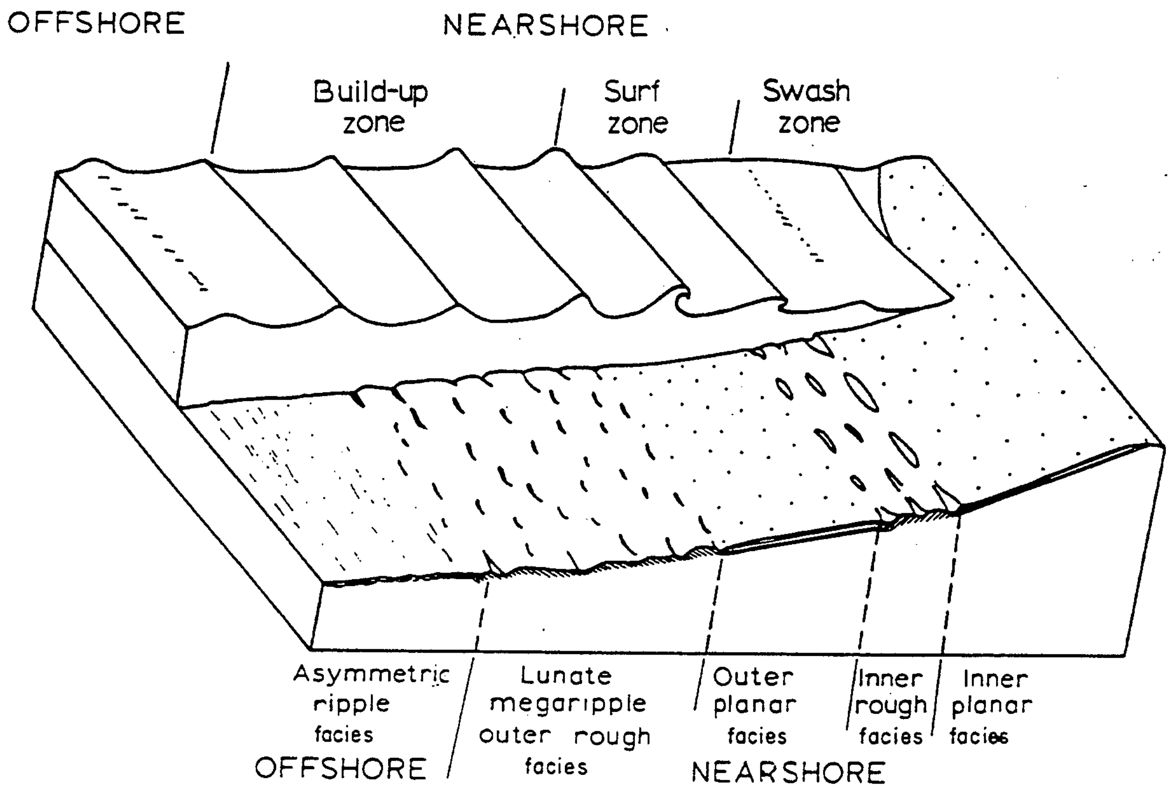

Figure 2. Megaripples have been observed in the outer rough facies and the inner rough facies of a high-energy nearshore (Clifton *et al.*, 1971).

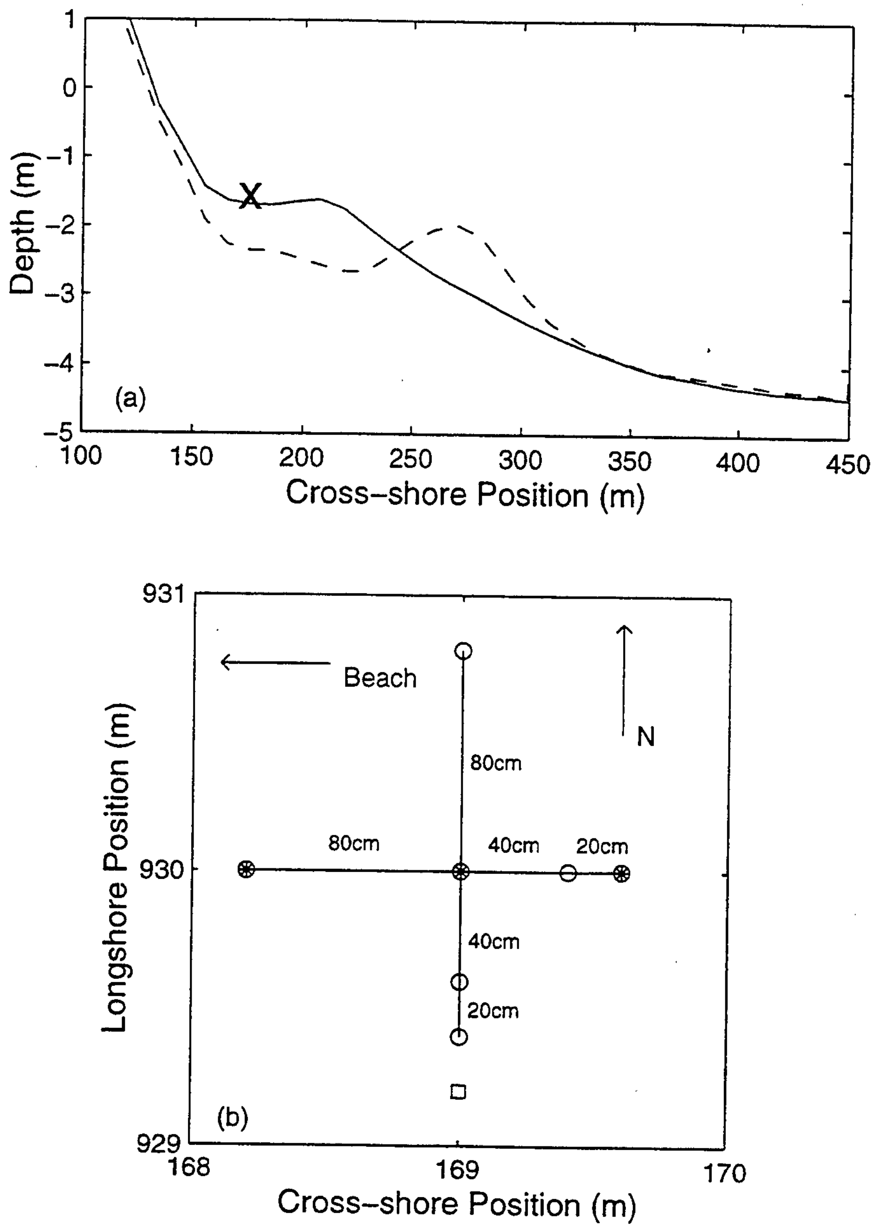

Figure 3. Location of the altimeter array. (a) X shows the location of the array in the trough between the sandbar and the beach. The array was approximately 50 m from the shoreline. Profiles were from 01 SEP 1994 (solid curve) and 15 OCT 1994 (dashed curve). (b) The plan view of the altimeter array shows the location of the AGC altimeters (circles), the electromagnetic current meter (square), and the three altimeters used in Figure (9) time series (asterisks).

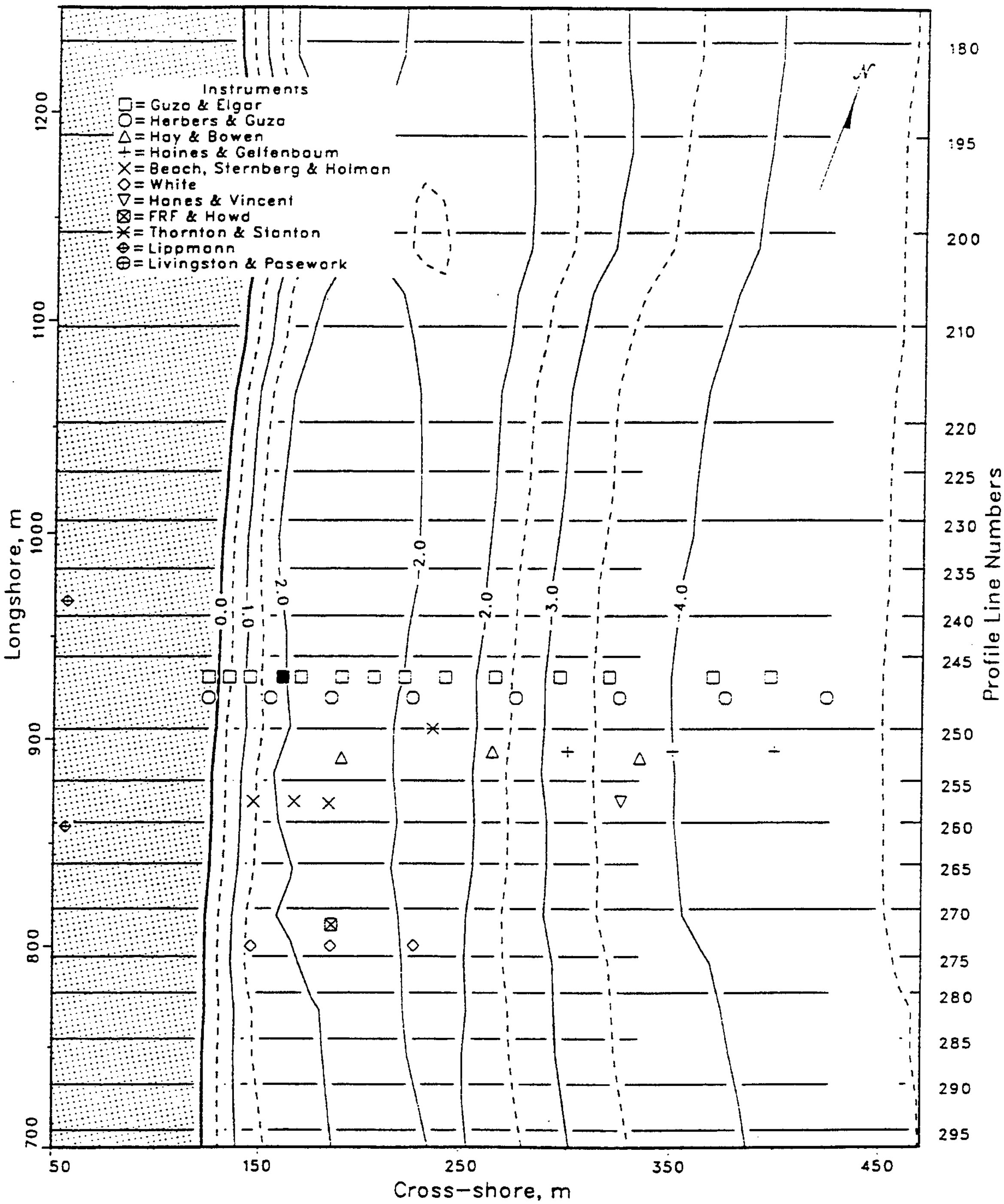

Figure 4. Bathymetry and DUCK94 instrument layout for 04 OCT 1994. Shaded square indicates location of the altimeter array.

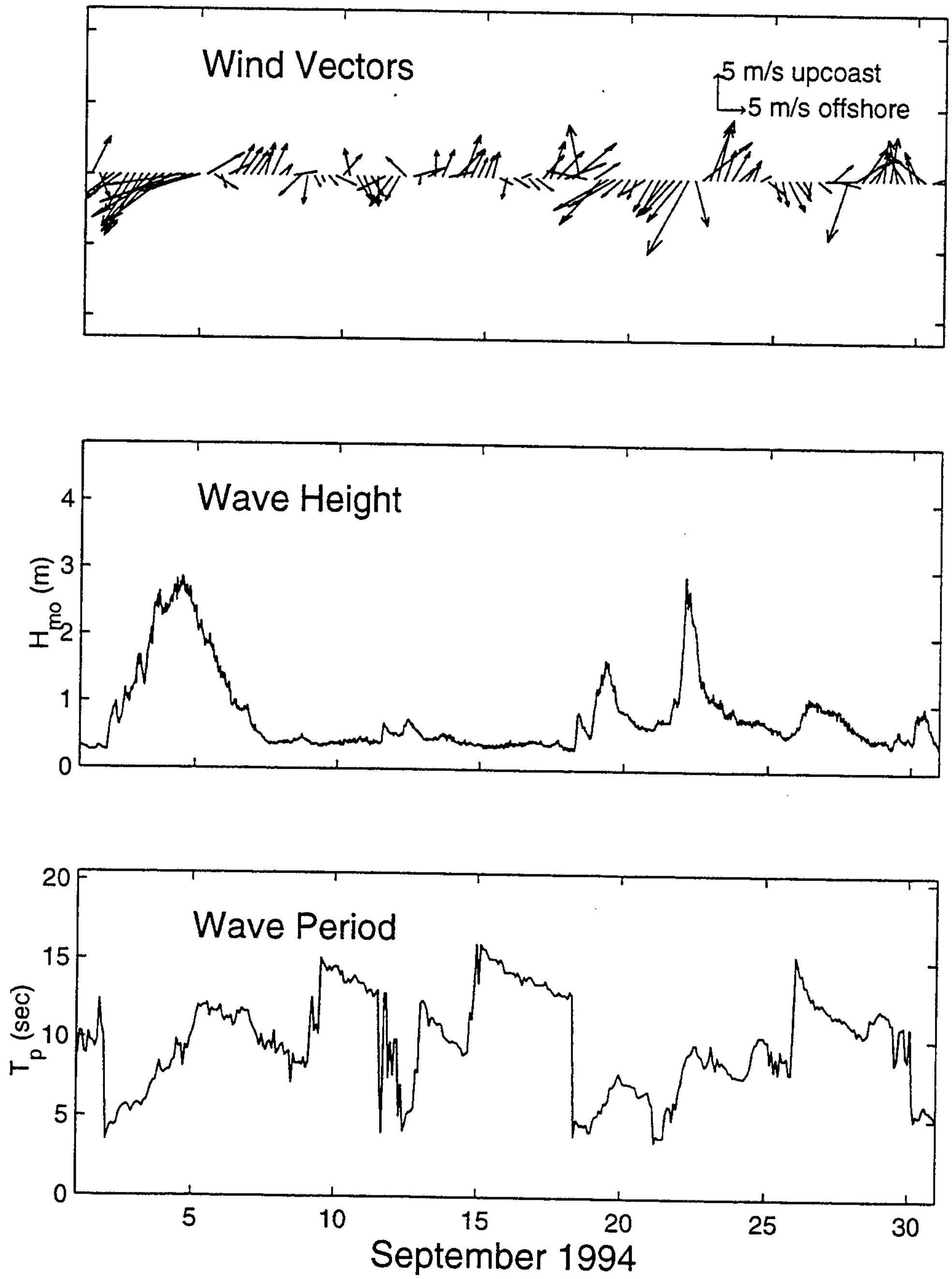

Figure 5. Climatology during September for the DUCK94 experiment. H_{mo} is the spectral estimate of the significant wave height. T_p is the period of the peak frequency measured in 8 m depth.

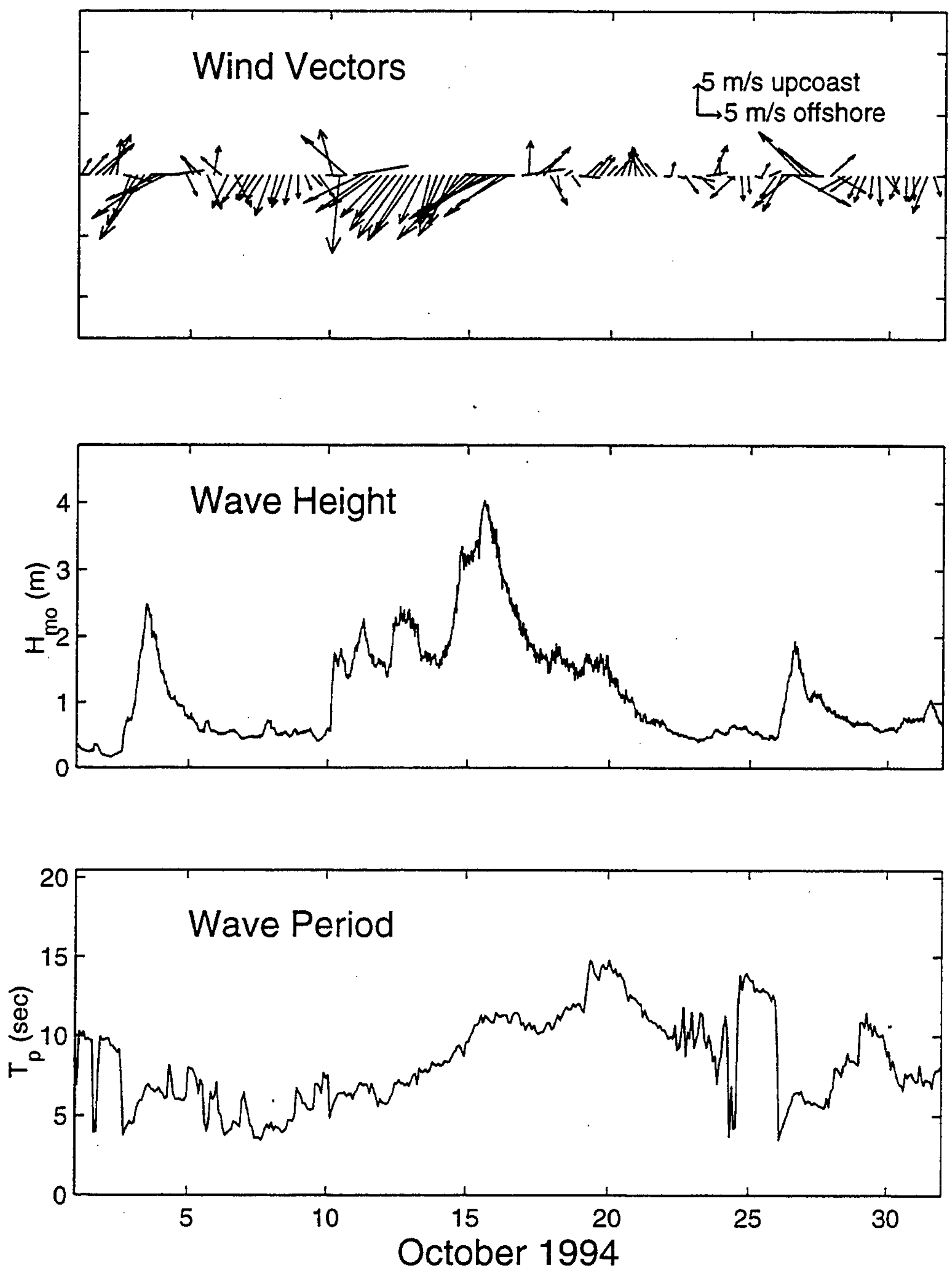

Figure 6. Climatology during October for the DUCK94 experiment. H_{mo} is the spectral estimate of the significant wave height. T_p is the period of the peak frequency measured in 8 m depth.

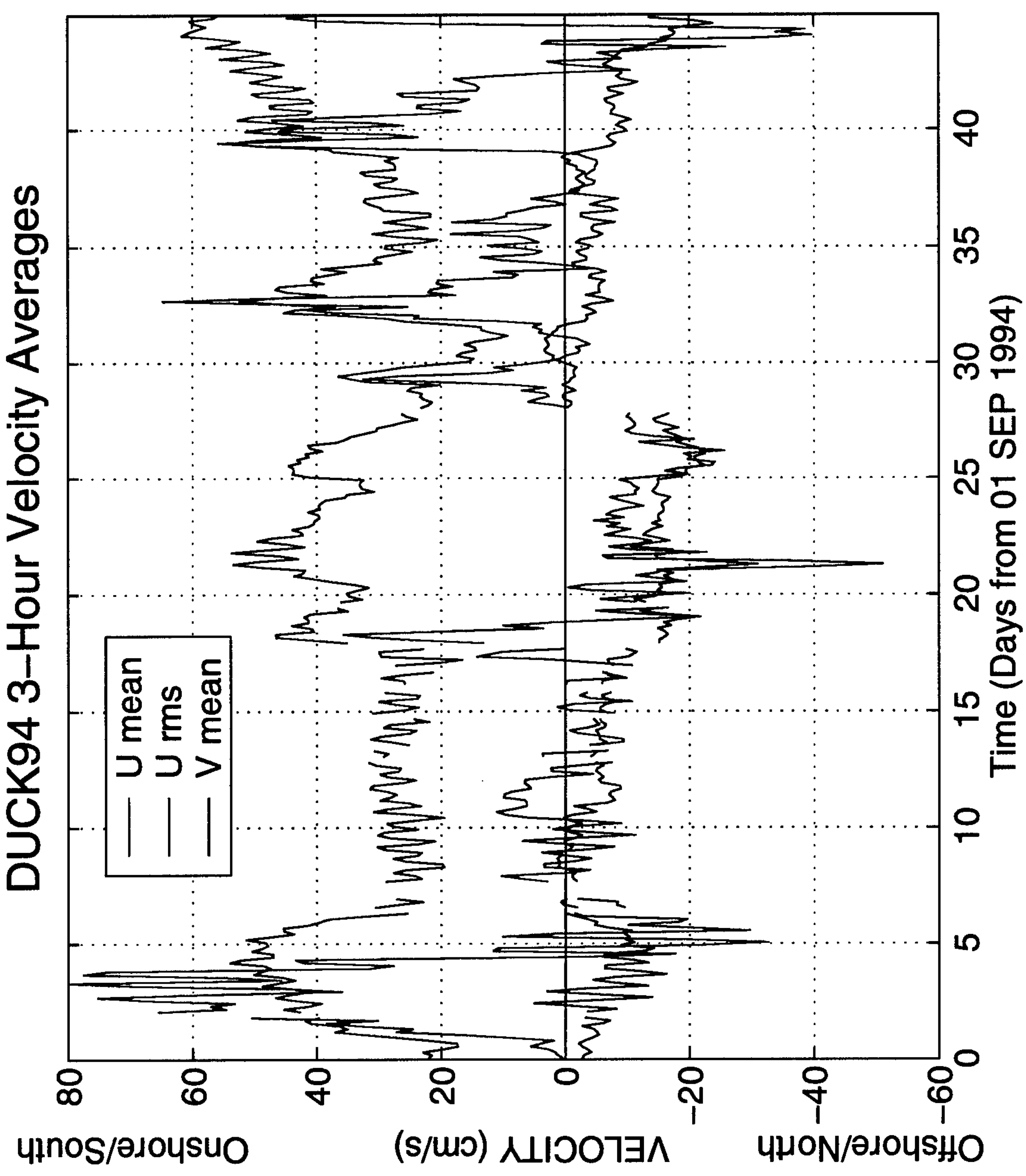

Figure 7. Three hour averages of the instantaneous fluid velocity components from 01 SEP 1994 to 15 OCT 1994. Positive values indicate onshore or southerly flow and negative values indicate offshore or northerly flow.

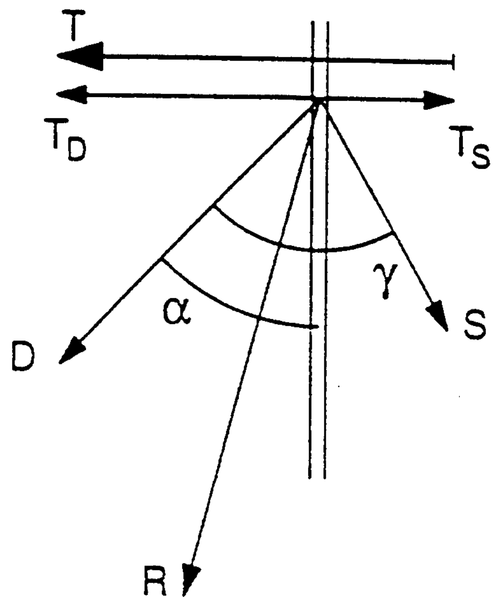

Figure 8. Transport vector example (Gallagher *et al.*, 1998b) where γ is the angle between the dominate, *D*, and subordinate, *S*, transport vectors. α is the angle between *D* and the bedform crest (double line). *R* is the vector sum of *D* and *S*. $T = |T_D| + |T_S|$ is the gross bedform normal transport.

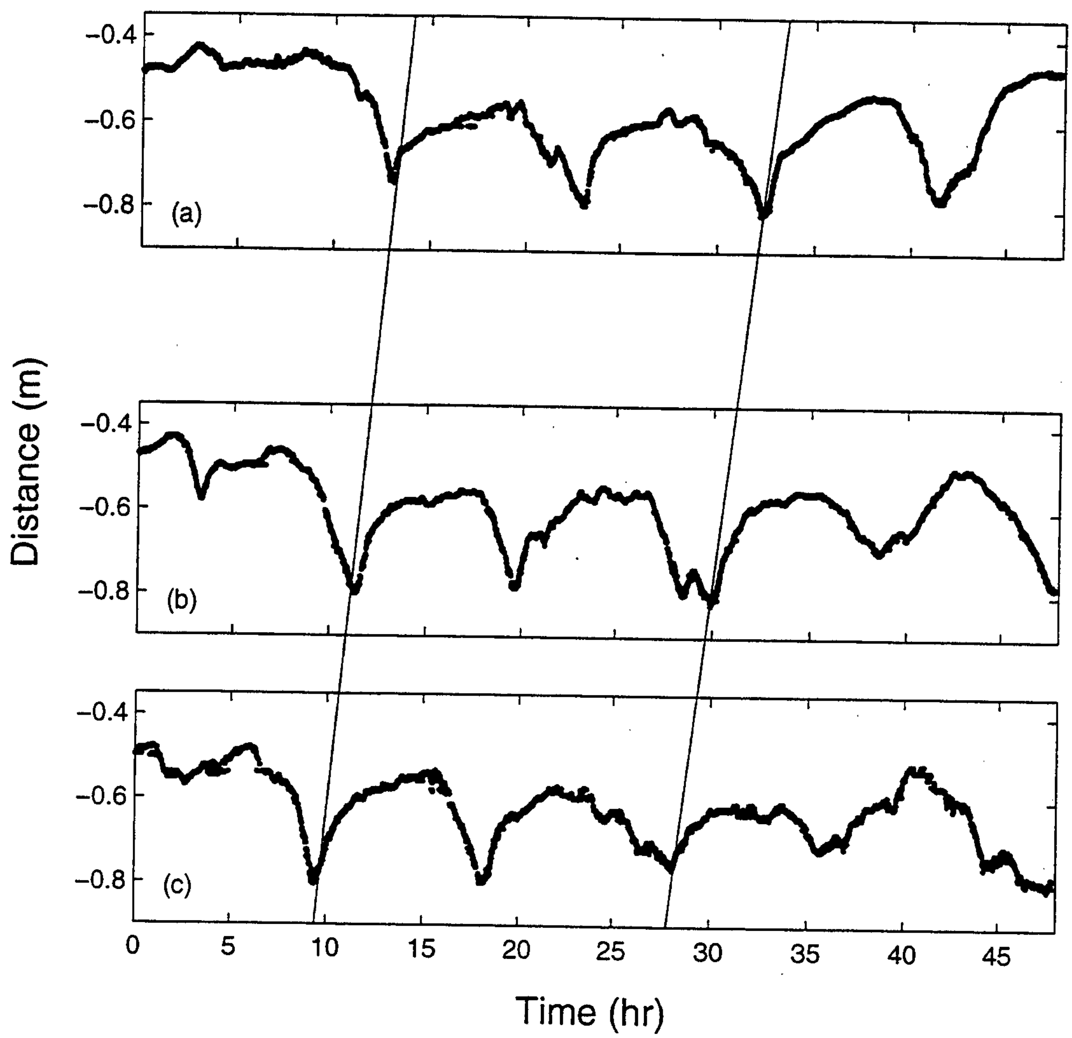

Figure 9. Migrating megaripples are seen in this time series example from three altimeters (asterisks in Figure 3b) where (a) is from the most onshore altimeter. The slopes of the lines connecting the troughs of the bedforms illustrate onshore migration on O(30 cm/hr) (Gallagher *et al.*, 1998b).

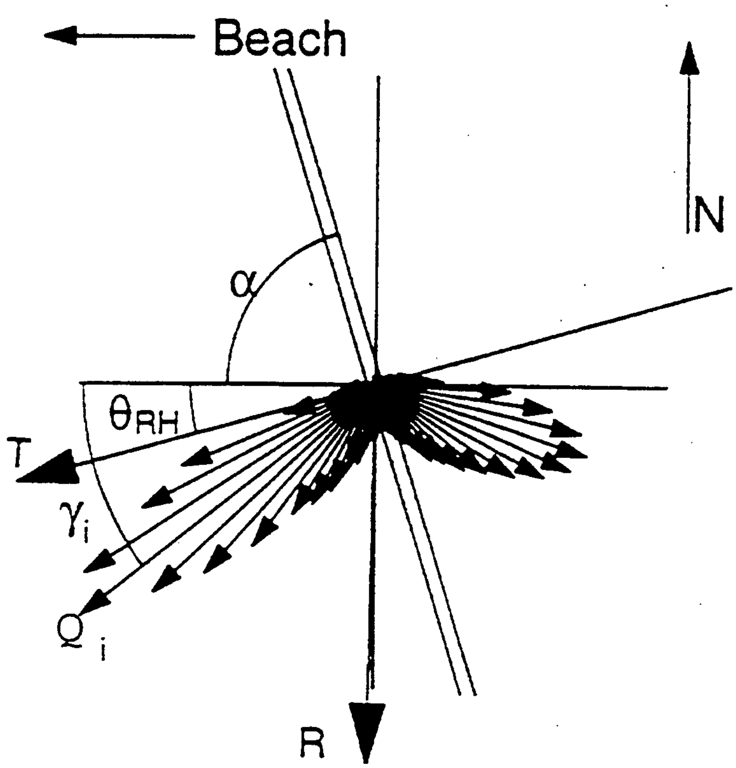

Figure 10. Example of predicted bedform orientation where the magnitude and direction of each cumulative transport vector are given by Q_i and γ_i, respectively. α is the orientation of the bedform crest (double line) such that the gross bedform normal transport, T, is maximized. $\theta_{RH} = 90° - \alpha$. The direction of the resultant vector, R, is included for comparison (Gallagher *et al.*, 1998b).

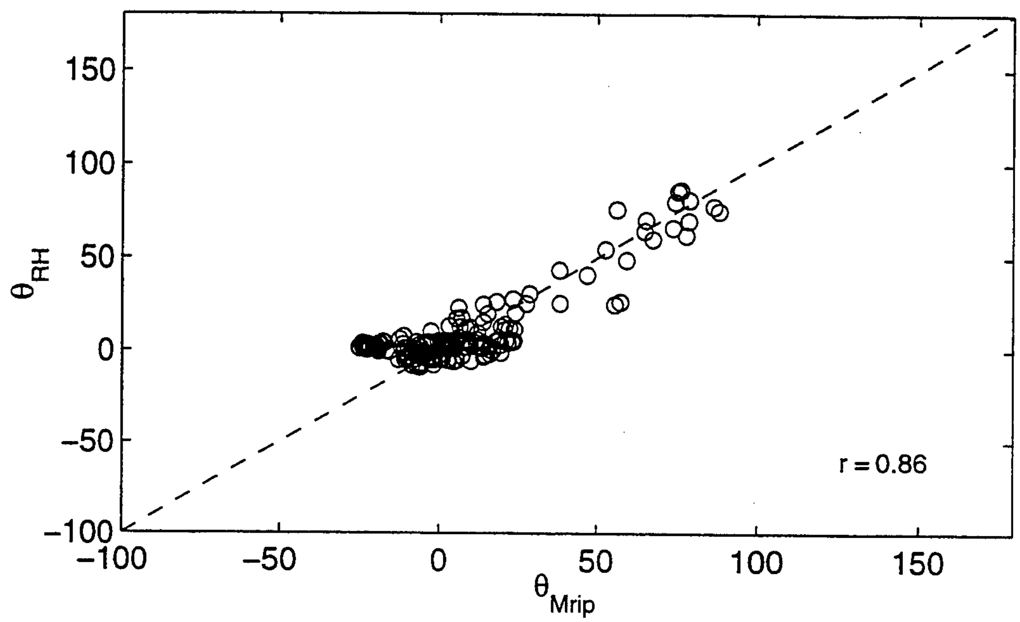

Figure 11. Predicted megaripple migration direction, θ_{RH}, versus observed megaripple migration direction, θ_{Mrip}, where 0° is onshore and 90° is to the south and r is the correlation coefficient (Gallagher *et al.*, 1998b).

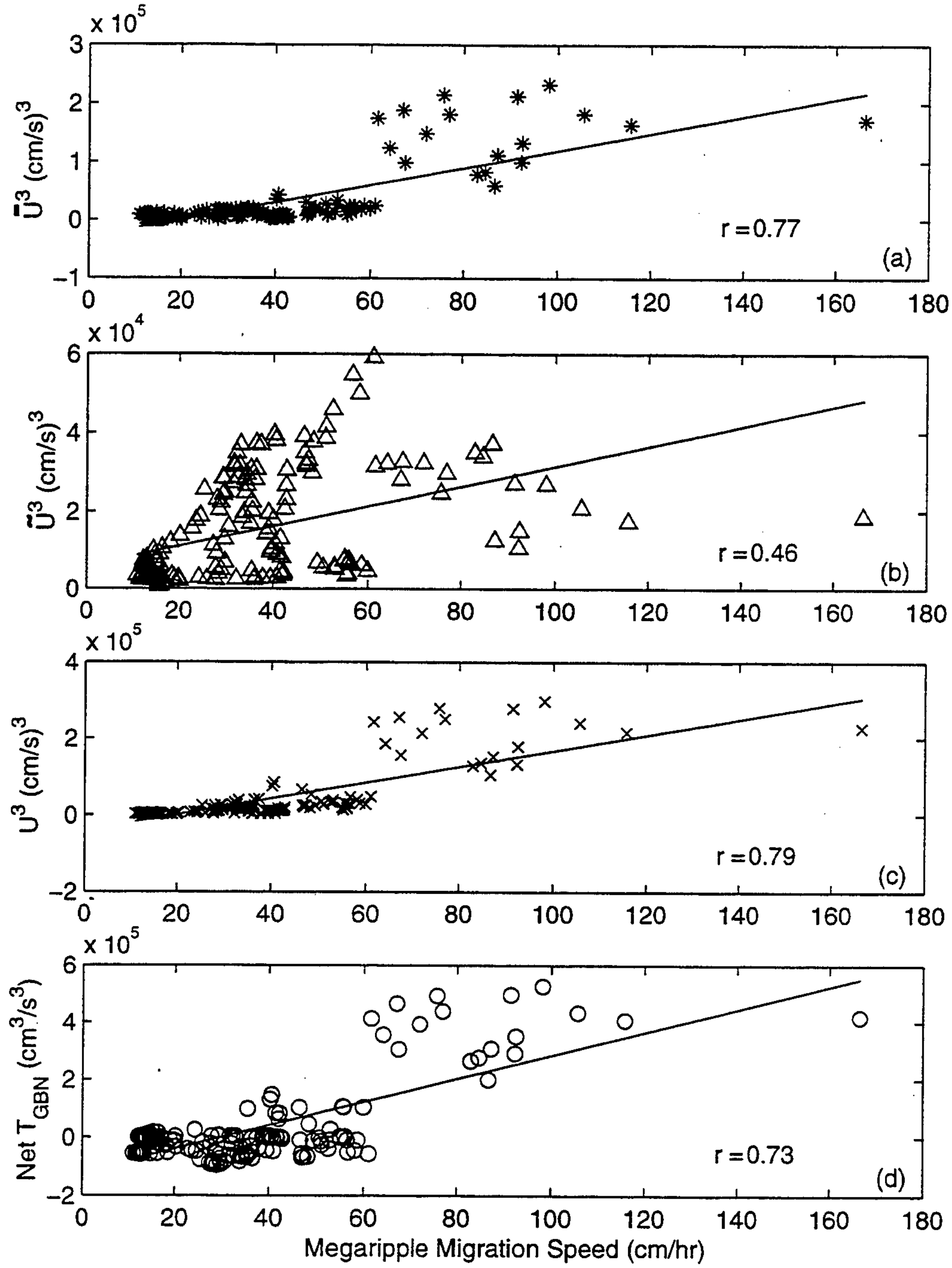

Figure 12. Comparison between observed megaripple migration speeds and the cube of the (a) mean, $\bar{U}$, (b) skewness-weighted rms wave, $\tilde{U}$, and (c) vector sum, U, in addition to (d) the predicted *net gross bedform normal transport*, *Net* T_{GBN}.

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5. Dr. Edith. L. Gallagher 2
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   Naval Postgraduate School
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